Predictions of gamma-ray emission from classical novae and their detectability by CGRO

M. Hernanz[1], J. Gómez-Gomar[1], J. José[2] and J. Isern[1]

[1] *Institut d'Estudis Espacials de Catalunya (IEEC), CSIC Research Unit*
Edifici Nexus-104, C/Gran Capita 2-4, 08034 Barcelona, SPAIN
[2] *Departament de Física i Enginyeria Nuclear (UPC)*
Avda. Víctor Balaguer s/n, 08800 Vilanova i la Geltrú, SPAIN

Abstract. An implicit hydrodynamic code following the explosion of classical novae, from the accretion phase up to the final ejection of the envelope, has been coupled to a Monte-Carlo code able to simulate their gamma-ray emission. Carbon-oxygen (CO) and oxygen-neon (ONe) novae have been studied and their gamma-ray spectra have been obtained, as well as the gamma-ray light curves for the important lines (e^-–e^+ annihilation line at 511 keV, ^{7}Be decay-line at 478 keV and ^{22}Na decay-line at 1275 keV). The detectability of the emission by CGRO instruments has been analyzed. It is worth noticing that the γ-ray signature of a CO nova is different from that of an ONe one. In the CO case, the 478 keV line is very important, but lasts only for ~2 months. In the ONe case, the 1275 keV line is the dominant one, lasting for ~ 4 years. In both cases, the 511 keV line is the most intense line at the beginning, but its short duration (~2 days) makes it very difficult to be detected. It is shown that the negative results from the observations made by COMPTEL up to now are consistent with the theoretical predictions. Predictions of the future detectability by the INTEGRAL mission are also made.

INTRODUCTION

Nova explosions are caused by thermonuclear runaways on white dwarfs accreting hydrogen from a main sequence companion in a cataclysmic variable. The explosive burning of hydrogen on the top of a CO or an ONe degenerate core leads to the synthesis of some β^+ unstable nuclei, such as ^{13}N, ^{14}O, ^{15}O, ^{17}F and ^{18}F. These nuclei have short lifetimes (~1-2 minutes for ^{14}O, ^{15}O and ^{17}F, ~15 min for ^{13}N and ~3 hours for ^{18}F), and they emit a positron when they decay. These positrons annihilate with electrons leading to the emission of photons with energy less or equal to 511 keV. Furthermore, other medium- and long-lived radiocative nuclei are synthesized in classical novae: ^{7}Be (τ=77days), whichs emits a photon of 478 keV after an electron capture, ^{22}Na (τ=3.75yr) and ^{26}Al (τ=1.04$\times$10^6 yr), which

experience a β^+-decay emitting photons of 1275 and 1809 keV, respectively. Thus, classical novae are potential γ-ray emitters, as was pointed out in previous works (Clayton & Hoyle [1], Clayton [2], Leising & Clayton [3]). There are also some previous works concerning nucleosynthesis in classical novae (see Politano et al [4], Prialnik & Kovetz [5] and references therein for nucleosynthesis in ONe and CO novae, respectively, as well as Hernanz et al [6], José et al [7], José & Hernanz [8] and [9]). But to our knowledge there are no previous works which follow all the phases (from the accretion stage to the final explosion and mass ejection phases) and couple them to the study of the γ-ray emission of classical novae.

In this paper we have used realistic profiles of densities, velocities and chemical compositions (obtained by means of a hydrodynamical code) to determine the production and transfer of γ-rays (by means of a Monte-Carlo code) during nova explosions. In this way, we are able to do a detailed analysis of the γ-ray emission of classical novae and predict their detectability by instruments onboard the CGRO (see our previous paper by Hernanz et al [10] for our first results and their relation to the future mission INTEGRAL). We are mainly concerned by the emission and potential detectability of individual novae, related to the decay of the medium-lived nuclei ^{7}Be and ^{22}Na (besides of the short-lived nuclei ^{13}N and ^{18}F).

γ-RAY SPECTRA AND LIGHT CURVES OF CO AND ONE NOVAE

In table 1 we present the main properties of the ejecta of some of the most representative models we have computed (accretion rate 2×10^{-10}M$_\odot$.yr^{-1}). There is an important difference between CO and ONe novae: CO novae are important producers of ^{7}Be (thus line emission at 478 keV is expected during some days), whereas ONe novae are important producers of ^{22}Na (thus line emission at 1275 keV during the first years after the explosion is expected). This can clearly be seen by comparing the γ-ray spectra of a typical CO nova (CO1) and those of an ONe one (ONe2), shown in figure 1 for different epochs after the explosion. In all cases a continuum component, mainly below 511 keV, appears as well as some lines (511 keV in all cases and 478 keV and 1275 keV in CO and ONe novae, respectively). Two phases can be distinguished in the evolution of all models. During the early expansion, the ejected envelope is optically thick and there is an important contribution of the continuum below 511 keV, related to the comptonization of 511 keV photons. Later on, when the envelope becomes optically thin, absorption and comptonization become negligible; therefore, the intensity of the lines is exclusively determined by the total mass of the radioactive nuclei ^{7}Be (CO novae) and ^{22}Na (ONe novae). The main properties of the lines are shown in table 2. It is worth noticing that fluxes are rather low, due to the small ejected masses (see table 1). This explains the null results of the observations of the 1275 keV emission by some novae made with COMPTEL onboard CGRO (Iyudin et al [12]). Our predicted fluxes are fully compatible with the upper limits obtained in that work. It is also worth noticing

TABLE 1. Main properties of the ejecta one hour after peak temperature. Initial mass, total ejected mass and ejected mass of the most relevant radioactive nuclei are in $M_\odot$ and the mean kinetic energy of the ejecta, $< E_k >$, is in erg.g^{-1}

Model	M_{WD}	M_{ejec}	$< E_k >$	^{7}Be	^{13}N	^{18}F	^{22}Na
ONe1	1.15	$1.8\ 10^{-5}$	$3.1\ 10^{16}$	~ 0	$5.5\ 10^{-9}$	$7.1\ 10^{-8}$	$9.8\ 10^{-10}$
ONe2	1.25	$1.6\ 10^{-5}$	$3.3\ 10^{16}$	$1.2\ 10^{-11}$	$2.9\ 10^{-8}$	$6.7\ 10^{-8}$	$1.6\ 10^{-9}$
CO1	0.8	$6.3\ 10^{-5}$	$8\ 10^{15}$	$7.8\ 10^{-11}$	$1.6\ 10^{-7}$	$1.7\ 10^{-7}$	~ 0
CO2	1.15	$1.4\ 10^{-5}$	$3.2\ 10^{16}$	$1.1\ 10^{-10}$	$1.3\ 10^{-8}$	$3.6\ 10^{-8}$	~ 0

TABLE 2. Properties of the 511 keV line (columns 2 and 3) and of the 1275 and 478 keV lines (columns 5 and 6): time and flux (d=1kpc) at maximum.

Model	t [hours]	$Flux_{511}$ [photons/s/cm^2]	line	t [days]	Flux [photons/s/cm^2]
ONe1	6	$1.3\ 10^{-2}$	1275 keV	7.5	$3.8\ 10^{-6}$
ONe2	5	$1.6\ 10^{-2}$	1275 keV	6.5	$6.1\ 10^{-6}$
CO1	7.5	$1.4\ 10^{-4}$	478 keV	13	$1.4\ 10^{-6}$
CO2	6.5	$7.3\ 10^{-3}$	478 keV	5	$2.6\ 10^{-6}$

the important fluxes associated with the 511 keV line that we predict for all models (see table 2). This flux should be detected by the current instruments onboard the CGRO, provided that novae are observed very early after their explosion. A retrospective analysis of the BATSE data would perhaps provide important clues to this issue (see Fishman et al [13]).

We want to mention that there is a lack of agreement between all the theoretical models of novae (including ours) and some observations of ejected masses of classical novae, although large uncertainties affect sometimes the determination of observed ejected masses. For instance, our model ONe1 fits quite well the observed abundances of the neon nova QU Vul 1984, but observations of this nova give an ejected mass that can reach $\sim 10^{-3} M_\odot$(Saizar et al 1992), almost two orders of magnitude larger than the theoretical one. Thus the flux of the 1275 keV line could be considerably larger, but no theoretical models are by now able to produce simultaneously such large ejected masses and neon in the ejecta.

In figure 2 we show the light curves of the 478 and 1275 keV lines for CO and ONe models, respectively. For the 478 keV line two different phases can be distinguished: during the first ~1.5 days, the line is completely dominated by the continuum generated by ^{13}N and ^{18}F decays, whereas later on the line follows the typical light curve of the ^{7}Be radioactive decay, with τ=77 days. The 1275 keV line has a rise phase lasting ~7days, followed by a decline related to the decay of ^{22}Na. The small fluxes obtained make it impossible to detect this line with the current CGRO instruments, unless a very close explosion occurs (the same as for the future SPI instrument onboard INTEGRAL).

Concerning the light curve of the 511 keV line for all the models, as several isotopes, with different decay timescales, contribute to this emission, its temporal evolution is somewhat complex. Besides one very early maximum appearing in the

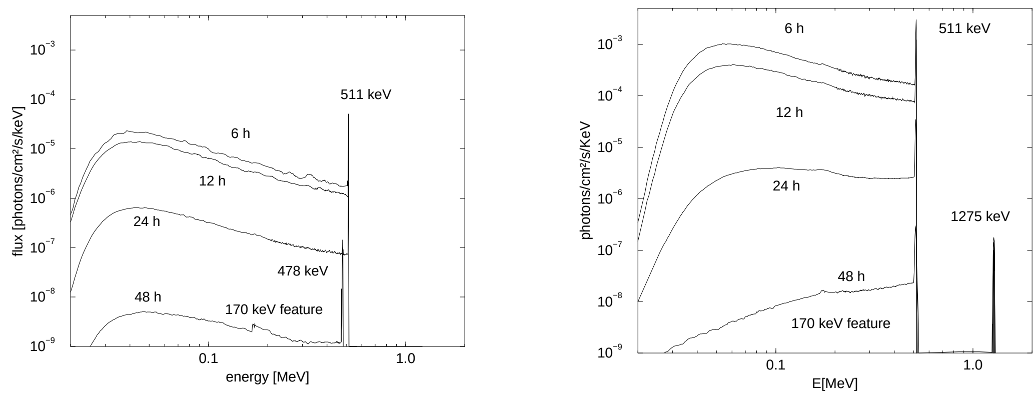

FIGURE 1. Evolution with time of the γ-ray spectrum of a CO nova of 0.8 $M_\odot$(left) and an ONe nova of 1.25 $M_\odot$(right).

CO novae (related to ^{13}N decay), one later maximum appears in all cases at ~ 6 hours (see table 2), which is related to ^{18}F decay. The further development of the light curves is different in the CO and in the ONe cases: in the ONe case, as ^{22}Na emits a e^+ when it decays, the emission at 511 keV lasts for a longer time (as the ^{22}Na decay- timescale is much longer than the ^{18}F one). An early observation of a nova explosion, either of a CO or an ONe one, would provide a positive detection of the 511 keV line (an estimation of the detection distance of our novae by the future SPI instrument onboard INTEGRAL yields around 10 kpc for all of them except for the low-mass CO1 model).

CONCLUSIONS

We have developed a Monte-Carlo code in order to treat the production and transfer of γ-rays in nova envelopes, coupled to a hydrodynamical code that provides realistic profiles of all the relevant magnitudes. Thus a complete view of the nova explosion is obtained. The most relevant features of the γ-ray emission of classical novae are their intense 511 keV emission, lasting only some hours, the 478 keV emision in the case of CO novae, related to ^{7}Be decay, and the 1275 keV emission in the case of ONe novae, related to ^{22}Na decay. The 1275 keV emission is the most long-lived one, but the fluxes obtained are too low to be detected for novae at typical distances, thus explaining the negative detections of the novae observed up to now by COMPTEL.

We thank for partial support the CICYT and DGICYT Projects ESP95-0091 and PB94-0827-C02-02.

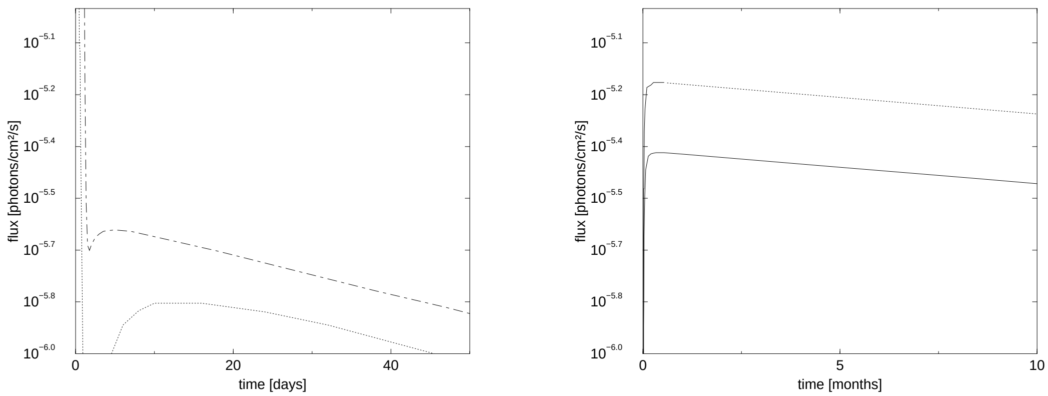

FIGURE 2. Left: Light curves of the 478 keV line (d=1 kpc) for CO novae (CO1: dotted, CO2: dot-dashed). Right: Light curves of the 1275 keV line (d=1 kpc) for ONe novae (ONe1: solid, ONe2: dotted)

REFERENCES

1. Clayton, D.D., and Hoyle, F. *ApJ* **187**, L101 (1974).
2. Clayton, D.D., *ApJ* **244**, L97 (1981).
3. Leising, M., and Clayton, D.D., *ApJ* **323**, 159 (1987).
4. Politano M., Starrfield S., Truran J.W., Weiss A., Sparks W.M., *ApJ* **448**, 807 (1995).
5. Prialnik D., Kovetz A., *ApJ* **477**, 356 (1997).
6. Hernanz M., José J., Coc A., Isern J., *ApJ Letters* **465**, L27 (1996).
7. José J., Hernanz M., Coc A., *ApJ Letters* **479**, L55 (1997).
8. José J., Hernanz M., *Nuclear Physics*, in press (1997).
9. José J., Hernanz M., in preparation.
10. Hernanz M., Gómez-Gomar, J., José, J., and Isern, J., *The Transparent Universe*, ESA SP-382, Noordwijk: ESA Publications Division, 1997, pp. 47-50.
11. Saizar, P., et al, *ApJ* **398**, 651 (1992).
12. Iyudin A.F., et al, *A&A* **300**, 422 (1995).
13. Fishman G.J., et al, *Gamma-Ray Line Astrophysics*, New York: AIP, 1991, pp. 190-192.